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Research of Loading of a Hopper Container During Sea Transportation by a Train Ferry

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ABSTRACT: The efficiency of freight transportation can be improved by the use of hopper containers. If required they can be equipped with lift-off roofs, which makes it possible to transport the freight requiring protection from weather. The possibility to transport these containers by sea was studied through their loading. The research included the case when a hopper container was part of the combined train and transported by the train ferry. It was taken into account that the container was loaded with bulk freight. The pressure to the container walls was determined with the Coulomb method. The value of the pressure from the bulk freight was included in the strength calculation. It was found that the maximum equivalent stresses in the container structure did not exceed the allowable values. The study also included the determination of the container stability relative to the flat wagon frame during sea transportation. It was found that with consideration of the typical diagram of interaction between the container and the flat wagon frame the equilibrium stability of the container was provided at the rolling angles up to 26°.

1 INTRODUCTION

The competitiveness of railway transport can be maintained by means of the introduction of combined transport systems in operation. As known, one of the most promising and widespread one is container transportation.

The efficiency of container transportation can be improved by means of designing promising container structures intended for transportation of a wide range of freight. The designing of such containers requires taking into account the potential loads that affect the containers during their transportation by rail, road, air, sea, and also if they are included in combined trains transported by train ferries (Fig. 1). Such combined transportation has developed when the transport corridor New Silk Road connecting Ukraine and China was put into operation, which has made it possible to transport combined trains by ferries.

Therefore, the issue of designing new container structures with improved technical and operational characteristics and calculating the loading on them if they are included in combined trains requires thorough investigation.

The designing of new container structures requires taking into account a wide range of potential loads in operation. These loads depend not only on the operational conditions but also on types of freight they transport: package, bulk, pallet freight, etc.

a) 

b) 

Figure 1. Train ferry transportation. a) Train ferry Heroes of Odessa [1]; b) Rolling Wagons onto a Train Ferry [2]

The special features of designing containers to transport long freight are described in article [3]. The strength calculation for the bearing structures of a container at the loads on the container walls from the tubes was made with the finite element method. However, the authors of the study mentioned did not discuss the issue of how to determine the pressure from the bulk cargo to the container walls.

The introduction of containers for fruit and vegetable transportation is substantiated in article [4]. It describes the main requirements for such containers. The results of strength calculation for the container frame at the operational loading modes were presented. However, the authors did not determine the pressure from the freight transported to the container walls.

The effect of the container weight to the metacenter height of the train ferry is studied in [5]. The algorithm to assess the effect of the location of the container weight center on the container carrier stability was proposed. But the authors did not study the container stability when transported by the train ferry.

The value of the pressure from the bulk cargo to the walls of an open car transported by the train ferry is determined in study [6]. The dynamic loading causing an additional effect to the sidewall of the car body was determined by means of differentiation of the law of sea wave motion. However, the authors did not study the pressure to the container walls during its sea transportation.

The effect of the bulk freight to the walls of a car body is assessed in [7]. The loading on the body was studied with the method of mathematical and computer modelling. But the author did not determine the pressure from the bulk freight to the container walls during train ferry transportation.

The techniques for loading and fastening steel rolls in containers for their train ferry transportation are studied in work [8]. The authors substantiated the implementation of the solutions proposed for ensuring the container stability during sea transportation. However, it should be noted that the authors did not study the stress state of the containers transported by sea.

Research into the dynamic loading on transport means, including containers as part of combined trains transported by sea, is presented in [9, 10]. The study provides the safety requirements for transport facilities during sea transportation. However, the determination of the stress state of transport means did not include the pressure from the bulk freight transported.

The analysis of the literature makes it possible to conclude that the issue of determination of the container loading is very important and requires further consideration to improve the operational efficiency.

The objective of the article is determination of the hopper container loading placed on the flat wagon transported by a train ferry. This will help to improve the safety and environmental friendliness of cargo transportation by the sea.

The following tasks were set to achieve the objective:

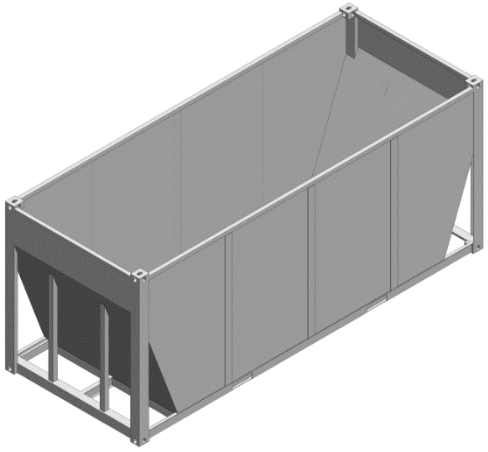
– a determination of the strength of a hopper container placed on the flat wagon during train ferry transportation; and
– a determination of the stability of a hopper container relative to the flat wagon frame during train ferry transportation.

2 PRESENTATION OF THE MAIN MATERIAL OF THE ARTICLE

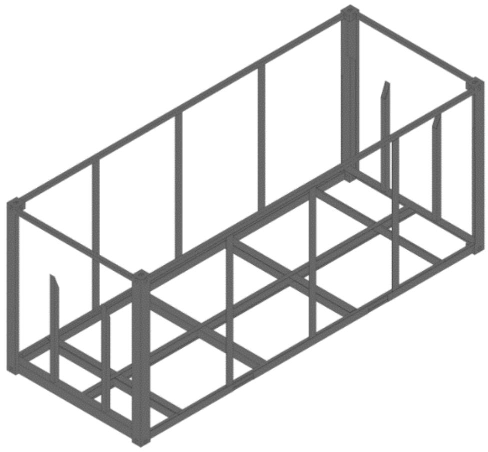
Higher efficiency of freight transportation can be achieved by means of hopper containers (Fig. 2).

A special feature of the container is its end walls at an angle of 30° to the vertical axis. Therefore, it can be discharged due to the gravity characteristics of the freight through the hatch doors (fig. 3). The container can be equipped with the lift-off roof for the freight requiring weather protection (fig. 4).

The transportability of the container by sea was studied by means of its loading. The research was made for the case if the container was included in the combined train and transported by the train ferry.



a)



b)

Figure 2. Hopper container. a) general view; b) framework

The stresses on the bearing structure of the container were determined with the finite elements in SolidWorks Simulation. The Mises criterion (the theory of energy transformation) was used as the design criterion [11, 12].

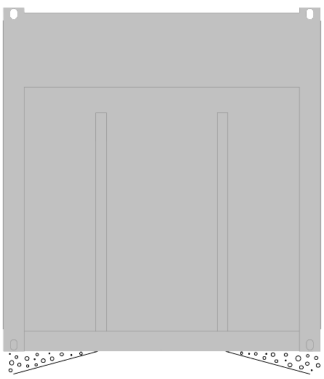


Figure 3. Diagram of the container discharge

The design diagram of the container is given in fig. 5. It was taken into account that the vertical load Pv and the pressure from the bulk freight Pp affected the container. The calculation was made for grain as the bulk freight because it is one of the most widespread types of bulk cargo transported in containers. Besides, the design model included the reactions Pf occurring in the container fittings to the dynamic loading during rolling. These reactions were applied to the fixed fittings on the side of the roll of the container.

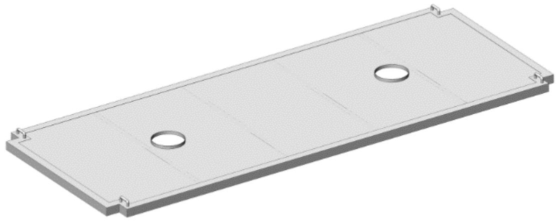


Figure 4. Lift-off roof of the container

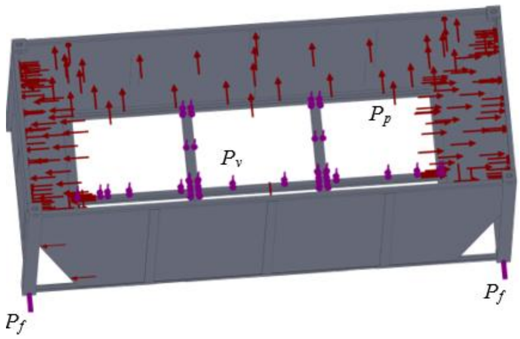


Figure 5. Design diagram of the container

The pressure to the container walls was determined with the Coulomb method [6]

$$p = G \cdot \frac{\sin(\vartheta - \rho)}{\sin(\vartheta + \psi - \rho)} \tag{1}$$

where
G is the weight of the prism of a freight shift;
ϑ is the plane inclination angle to the horizontal line;
ϱ is the internal friction angle (for ideal bulk environment it equals the natural slope angle);
δ is the friction angle between the freight and the wall.

It should be noted that the maximum pressure would correspond to the direction of the sliding plane. The value of the maximum pressure could be found with the method proposed by V. V. Synelnykov [6], according to which the variable ϑ – the plane inclination angle – should be replaced in the maximum pressure condition $(dp/d\vartheta) = 0$ with some variable x (in the research it is $\alpha = \theta$); in the general case it can be found analytically. Considering this condition, the formula for determination of the pressure from the bulk freight has the form

$$p = \gamma \cdot h \cdot \frac{\cos^2(\rho - \alpha)}{\left[1 + \sqrt{\frac{\sin\rho \cdot \sin\cdot(\rho - \alpha)}{\cos\alpha}}\right]^2 \cos\alpha}, \tag{2}$$

where
γ is the volume weight of the freight, kN/m^3;
h is the height of the open car body, m.

The design diagram of the container is given in Figure 6.

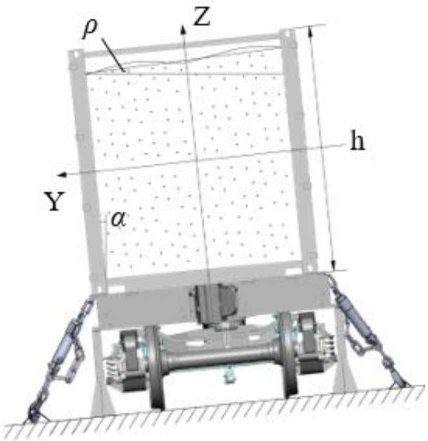


Figure 6. Design diagram for determination of the pressure from the bulk freight to the container walls

The angular displacements of the container relative to the longitudinal axis include the dynamic loading because it additionally affects the freight and the container walls. Therefore, the pressure from the bulk freight to the container walls was determined with the following formula:

$$p=\gamma\cdot h\cdot\frac{\cos^2(\rho-\alpha)}{\left[1+\sqrt{\frac{\sin\rho\cdot\sin\cdot(\rho-\alpha)}{\cos\alpha}}\right]^2\cos\alpha}+F_a, \tag{3}$$

where

F_a is the additional pressure conditioned by the dynamic loading to the bulk freight.

The value of the dynamic loading to the container and the bulk freight was determined by the method presented in [10]. For the case without displacements of the container relative to the flat wagon frame, the value of acceleration to it accounted for 0.25g. The calculation included a rolling angle of 12.2° conditioned by the static action of wind to the above-water projection of the ferry. As far as the value Fa was 4.26 kPa, the total pressure from the bulk freight equalled 11.6 kPa.

The finite element model of the container consisted of isoparametric tetrahedrons [13 – 17]. A graph-analytical method was used to determine the optimal number of grid elements [18 – 22]. The number of elements in the model was 112714, and the number of units – 37005. The maximum element size was 120 mm and the minimum – 24 mm.

The container was fixed in the zones of its interaction with the flat wagon. Low-alloyed Steel 09C2Cu was taken as the structural material. The calculation also included that the allowable stresses were equal to the yield limit of the material, i.e. 345 MPa. The results of the calculation are given in Figure 7.

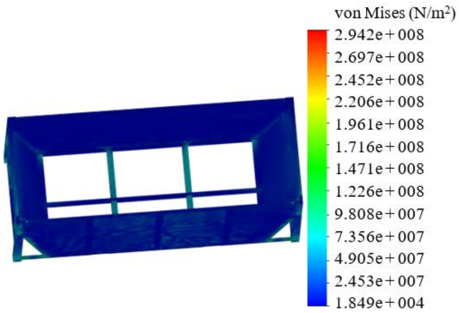


Figure 7. Stress state of the container

The maximum equivalent stresses in the container were recorded in the bottom side sill and were 294.2 MPa, which were lower than the allowable values [23] (Fig. 8). Thus, the strength of a container transported by sea and included in the combined train was ensured.

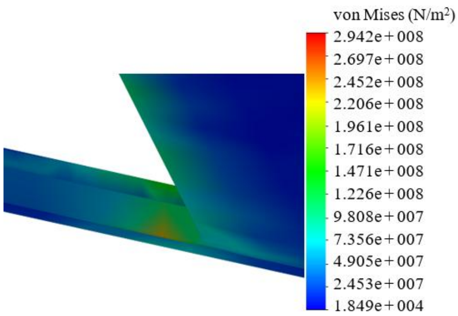


Figure 8. Maximum equivalent stresses in the container

The research also included the determination of the equilibrium stability of the container with consideration of the typical diagram of interaction with the flat wagon transported by the sea. The results of the calculation are given in Figure 9.

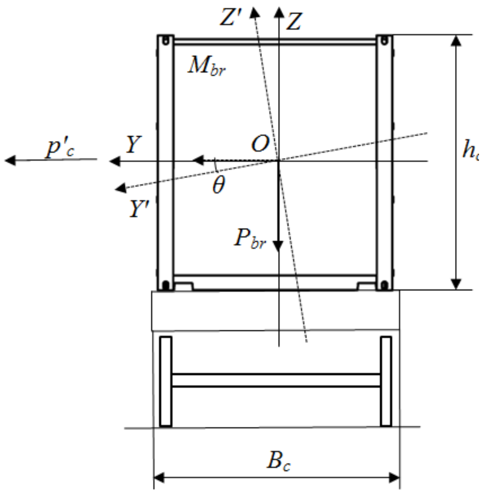


Figure 9. Design diagram for determination of the container stability

The container stability must meet the condition:

$$k_s=\frac{M_{ov}}{M_{rest}}=$$
$$=\frac{P_{br}\cdot\cos\theta\cdot\frac{B_c}{2}+n_f\cdot\left(M_{br}\cdot\left(g\cdot\sin\theta+\ddot{\theta}_c\right)\right)\cdot\frac{h_f}{2}}{p'_c\cdot\frac{h_c}{2}+M_{br}\cdot\left(g\cdot\sin\theta+\ddot{\theta}_c\right)\cdot\frac{h_c}{2}}\geq 1, \tag{4}$$

where
M_{ov} is the value of restoring moment;
M_{rest} is the value of overturning moment;
M_{br} is the gross mass of the container;
$\ddot{\theta}$ is the acceleration to the container at angular displacements relative to the longitudinal axis;
P_{br} is the gross weight of the container;
B_c is the container breadth;
n_f is the number of fixed fittings at which the container is supported at angular displacements relative to the longitudinal axis;
h_f is the height of a fixed fitting.

And the stability threshold reaches if the restoring moment equals the overturning moments, i.e. if $k_c = 1$.

The results of the calculation are given in Figure 10.

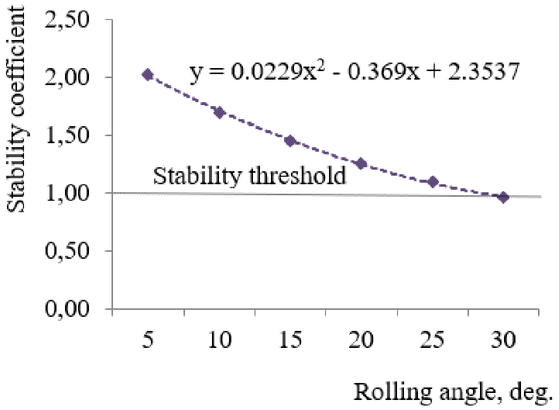


Figure 10. Dependency of the stability coefficient of the container on the rolling angle

It has been found that the container stability with consideration of the typical diagram of interaction with the flat wagon is provided at the rolling angles up to 26°.

The subject of this study is quite new, because the issue of transportation of combined trains by the sea has not received sufficient attention. This type of transportation entered operation in 2017 and it was a link in the route from Ukraine to China (the New Silk Road). Therefore, a comparative analysis of the achieved results with already known studies is not provided within the framework of this work.

It is important to note that the proposed calculation algorithm can also be used to study the loading of a container filled with another type of bulk cargo. In subsequent works, the authors will pay attention to this issue.

Further, as subsequent tasks being planned to solve by the authors within the framework of this study is an experimental assessment of the strength of a hopper container during transportation by the sea. Due to the difficulty of manufacturing an original design of such a container with real dimensions, it is assumed that full-scale tests will be carried out on a reduced-scale sample. Such a task can be implemented using the similarity method.

An equally important task in this area is to ensure the efficiency of the wagon braking system during their transportation by the sea. It is known that the braking system of the wagon coupling is connected to a special pneumatic system on a train ferry during transportation of wagons by the sea. When passing dangerous places in the water area, the coupling is braked by a pneumatic system. This allows increasing the safety of wagon transportation by the sea.

3 CONCLUSIONS

The research deals with determination of the strength of a hopper container placed on the flat wagon transported by the train ferry. The maximum equivalent stresses were recorded in the bottom side sill of the container and amounted to 294.2 MPa, which were lower than the allowable values. Thus the strength of a container included in the combined train transported by sea was ensured.

The research also includes determination of the stability of a hopper container relative to the flat wagon frame transported by the train ferry. It has been found that with consideration of the typical diagram of interaction between the container and the flat wagon frame the equilibrium stability of the container is provided at the rolling angles up to 26°.

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